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OpenMP: An Introduction

18-213/18-613: Introduction to Computer Systems
26th Lecture, April 21th, 2022

Very lightly adapted from Prof. Scott Baden's *Lecture 8,* CS-160, Winter 2016 @ CSE, UCSD

Announcements

- **Lab 7 (proxylab) checkpoint due today!**
  - Happy hacking!
  - Final submission due Thursday, April 28th
- Homework is on the usual schedule
  - Also due Thursday, April 28th.
- We have an early final exam: Monday, May 2nd @ 5:30pm ET
  - See Fall 2021 practice exams on Web site
  - Format and content will be similar
  - Counts BIG: 25% of final grade
    - Each 4 points = 1 point on final grade
  - Small Groups next week will help prepare
  - You'll need to review: It is comprehensive to "Day One"
  - Please let us know how we can help

Today

- **OpenMP Overview**

OpenMP

- A higher level interface for thread programming:
  - http://www.openmp.org
- Parallelization via source code annotations
- All major compilers support it, including gnu
  - https://gcc.gnu.org/wiki/openmp
- Compare with explicit threads programing

```
#pragma omp parallel private(i) shared(n)
{
#pragma omp for
for(i=0; i < n; i++)
    work(i);
}
```

```
int i0 = (n*TID)/NTHREADS;
int i1 = i0 + n/NTHREADS;

for (i=i0; i< i1; i++)
   work(i);
```

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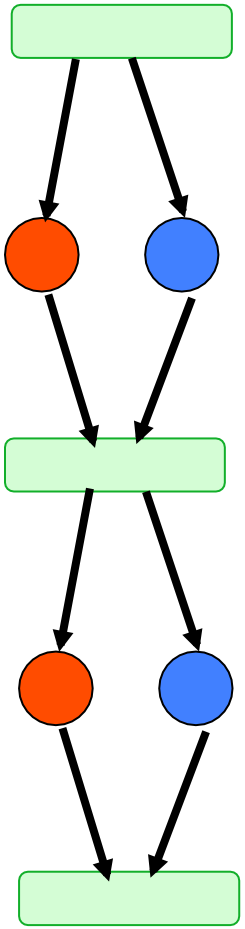
OpenMP's Fork-Join Model

- A program begins life as a single thread
- Enter a parallel region, spawning a team of threads
- The lexically enclosed program statements execute in parallel by all team members
- When we reach the end of the scope…
  - The team of threads synchronize at a barrier and are disbanded; they enter a wait state
  - Only the initial thread continues
- Thread teams can be created and disbanded many times during program execution, but this can be costly
- A clever compiler can avoid many thread creations and joins



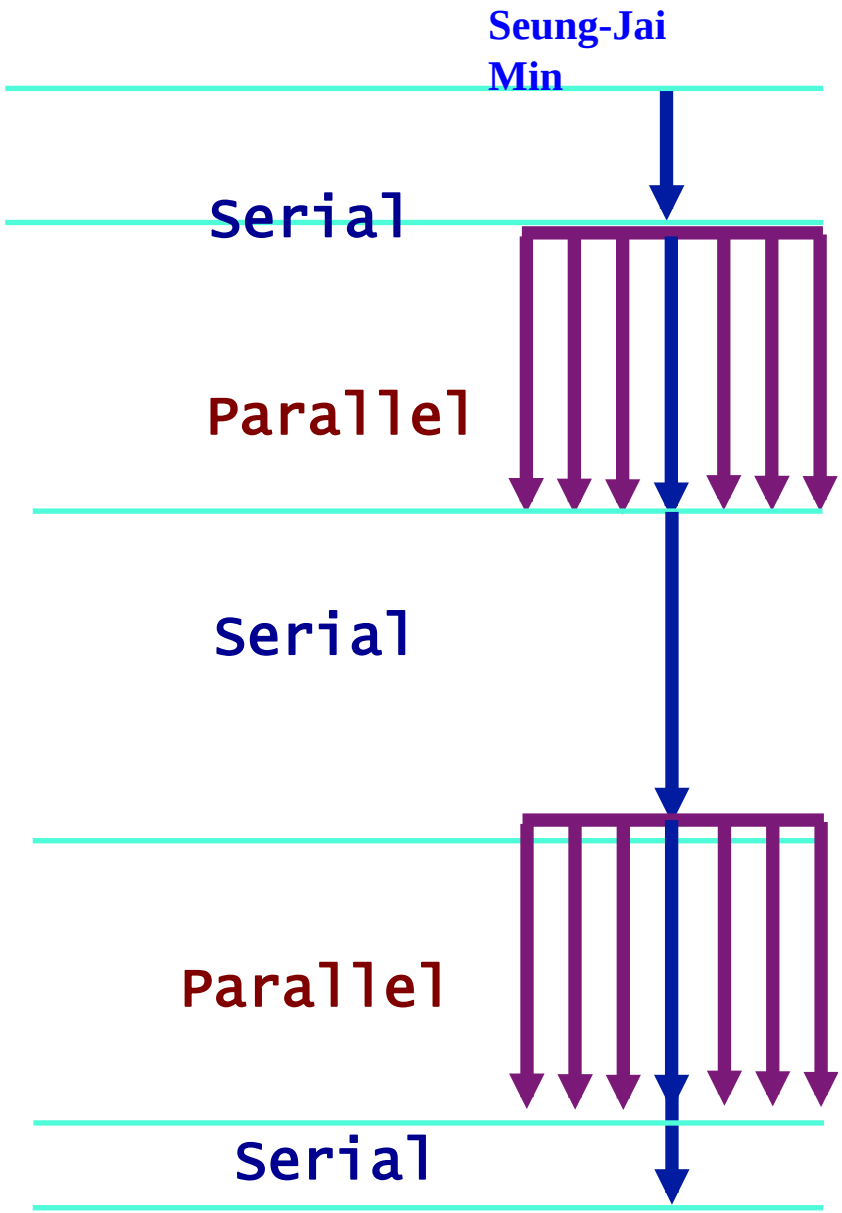
Fork join model with loops

```
cout << "Serial\n";
N = 1000;

#pragma omp parallel{
#pragma omp for
for (i=0; i<N; i++)
      A[i] = B[i] + C[i];

#pragma omp single
M = A[N/2];

#pragma omp for
for (j=0; j<M; j++)
      p[j] = q[j] - r[j];
}
cout << "Finish\n";
```



Loop parallelization

- The translator automatically generates appropriate local loop bounds
- Also inserts any needed barriers
- We use private/shared clauses to distinguish thread private from global data
- Handles irregular problems
- Decomposition can be static or dynamic

```
#pragma omp parallel for shared(Keys) private(i) reduction(&:done)
for  i = OE; i to N-2 by 2
    if (Keys[i] > Keys[i+1]) swap Keys[i] ↔ Keys[i+1];  done *= false; }
end do
return done;
```

Another way of annotating loops

- These are equivalent

```
#pragma omp parallel
{
#pragma omp for
    for (int i=1; i< N-1; i++)
        a[i] = (b[i+1] - b[i-1])/2h
}
```

```
#pragma omp parallel for
 for (int i=1; i< N-1; i++)
        a[i] = (b[i+1] - b[i-1])/2h
```

Variable scoping

- Any variables declared outside a parallel region are shared by all threads
- Variables declared inside the region are private
- Shared & private declarations override defaults, also usefule as documentation

```
int main (int argc, char *argv[]) {
   double a[N], b[N], c[N];  int i;

#pragma omp parallel for shared(a,b,c,N) private(i)
for (i=0; i < N; i++)
   a[i] = b[i] = (double) i;

#pragma omp parallel for shared(a,b,c,N) private(i)
for (i=0; i<N; i++)
c[i] = a[i] + sqrt(b[i]);
```

Dealing with loop carried dependences

- OpenMP will dutifully parallelize a loop when you tell it to, even if doing so "breaks" the correctness of the code

```
int* fib = new int[N];
   fib[0] = fib[1] =    1;
#pragma omp parallel for num_threads(2)
   for (i=2; i<N; i++)
       fib[i] = fib[i-1]+ fib[i-2];
```

- Sometimes we can restructure an algorithm, as we saw in odd/even sorting
- OpenMP may warn you when it is doing something unsafe, but not always

Why dependencies prevent parallelization

- Consider the following loops

```
#pragma omp parallel
{
#pragma omp for nowait
   for (int i=1; i< N-1; i++)
      a[i] = (b[i+1] – b[i-1])/2h

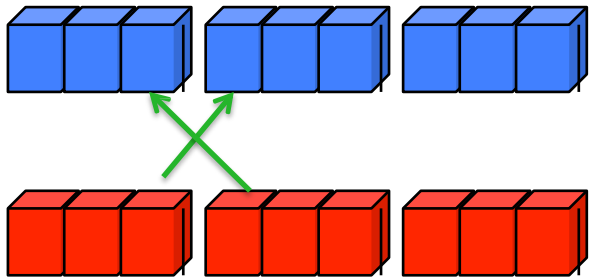
#pragma omp for
   for (int i=N-2; i>0; i--)
      b[i] = (a[i+1] – a[i-1])/2h
}
```

- Why aren't the results correct?

Why dependencies prevent parallelization

- Consider the following loops

```
#pragma omp parallel
{
#pragma omp for nowait
 for (int i=1; i< N-1; i++)
    a[i] = (b[i+1] – b[i-1])/2h
#pragma omp for
for (int N-2; i>0; i--)
    b[i] = (a[i+1] – a[i-1])/2h
}
```



- Results will be incorrect because the array a[ ], in loop #2, *depends* on the outcome of loop #1 (a *true dependence*)
  - We don't know when the threads finish
  - OpenMP doesn't define the order that the loop iterations wil be incorrect

Barrier Synchronization in OpenMP

- To deal with true- and anti-dependences, OpenMP inserts a barrier (by default) between loops:

```
for (int i=0; i< N-1; i++)
    a[i] = (b[i+1] – b[i-1])/2h
  BARRIER
for (int i=N-1; i>=0; i--)
    b[i] = (a[i+1] –a[i-1])/2h
```

- No thread may pass the barrier until all have arrived hence loop 2 may not write into b until loop 1 has finished reading the old values

- Do we need the barrier in this case? Yes

```
for (int i=0; i< N-1; i++)
    a[i] = (b[i+1] – b[i-1])/2h
  BARRIER?
for (int i=N-1; i>=0; i--)
     c[i] = a[i]/2;
```

Which loops can OpenMP parallellize, assuming there is a barrier before the start of the loop?

A. 1 & 2

B. 1 & 3

C. 3 & 4

D. 2 & 4

E. All the loops

1.
```
for i = 1 to N-1
    A[i] = A[i] + B[i-1];
```

2.
```
for i = 0 to N-2
    A[i+1] = A[i] + 1;
```

3.
```
for i = 0 to N-1 step 2
    A[i] = A[i-1] +A[i];
```

4.
```
for i = 0 to N-2{
    A[i] = B[i];
    C[i] = A[i] + B[i];
    E[i] = C[i+1];
}
```

All arrays have at least N elements

Which loops can OpenMP parallellize, assuming there is a barrier before the start of the loop?

A. 1 & 2

B. 1 & 3

C. 3 & 4

D. 2 & 4

E. All the loops

1. for i = 1 to N-1
A[i] = A[i] + B[i-1];

2. for i = 0 to N-2
A[i+1] = A[i] + 1;

3. for i = 0 to N-1 step 2
A[i] = A[i-1] +A[i];

4. for i = 0 to N-2{
A[i] = B[i];
C[i] = A[i] + B[i];
E[i] = C[i+1];
}

All arrays have at least N elements

How would you parallelize loop 2 by hand?

1. for i = 1 to N-1
   A[i] = A[i] + B[i-1];

2. **for i = 0 to N-2**
   A[i+1] = A[i] + 1;

How would you parallelize loop 2 by hand?

```
for i = 0 to N-2
    A[i+1] = A[i] + 1;
```

```
for i = 0 to N-2
    A[i+1] = A[0]  + i;
```

To ensure correctness, where must we remove the nowait clause?

A. Between loops 1 and 2
B. Between loops 2 and 3
C. Between both loops
D. D. None

```
#pragma omp parallel for shared(a,b,c) private(i)
      for (i=0; i<N; i++)
        c[i] = (double) i
#pragma omp parallel for shared(c) private(i) nowait
      for (i=1; i<N; i+=2)
          c[i] = c[i] + c[i-1]
#pragma omp parallel for shared(c) private(i) nowait
      for (i=2; i<N; i+=2)
          c[i] = c[i] + c[i-1]
```

To ensure correctness, where must we remove the nowait clause?

A. Between loops 1 and 2

B. Between loops 2 and 3

C. Between both loops

D. D. None

```
#pragma omp parallel for shared(a,b,c) private(i)
      for (i=0; i<N; i++)
        c[i] = (double) i
#pragma omp parallel for shared(c) private(i) nowait
      for (i=1; i<N; i+=2)
          c[i] = c[i] + c[i-1]
#pragma omp parallel for shared(c) private(i) nowait
      for (i=2; i<N; i+=2)
          c[i] = c[i] + c[i-1]
```

Exercise: Removing data dependencies

- How can we split this loop into 2 loops so that each loop parallelizes, and the result it correct?
  - B initially: 0 1 2 3 4 5 6 7
  - B on 1 thread: 7 7 7 7 11 12 13 14

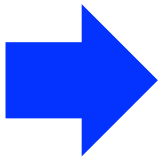
```
#pragma omp parallel for shared (N,B)
 for i = 0 to N-1
      B[i] += B[N-1-i];
```

B[0] += B[7], B[1] += B[6], B[2] += B[5]
B[3] += B[4], B[4] += B[3], B[5] += B[2]
B[6] += B[1], B[7] += B[0]

Splitting a loop

- For iterations i=N/2+1 to N, B[N-i] references newly computed data
- All others reference "old" data
- B initially: 0 1 2 3 4 5 6 7
- Correct result: 7 7 7 7 11 12 13 14

```
for i  = 0 to N-1
  B[i] += B[N-i];
```



```
#pragma omp parallel  for nowait
for i  = 0 to N/2-1
      B[i] += B[N-1-i];
for i  = N/2+1 to N-1
     B[i] += B[N-1-i];
```

Reductions in OpenMP

- In some applications, we reduce a collection of values down to a single global value
  - Taking the sum of a list of numbers
  - Decoding when Odd/Even sort has finished
- OpenMP avoids the need for an explicit serial section

```
int Sweep(int *Keys, int N, int OE, ) {
   bool done = true;

#pragma omp parallel for reduction(&:done)
   for (int i = OE; i < N-1; i+=2) {
      if (Keys[i] > Keys[i+1]) {
         Keys[i] ↔ Keys[i+1];
         done &= false;
      }
   }      //All threads 'and' their done flag into a local variable
          // and store the accumulated value into the global
   return done;
}
```

Reductions in OpenMP

- In some applications, we reduce a collection of values down to a single value
  - Taking the sum of a list of numbers
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 #pragma omp parallel for reduction(&:done)
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        if (Keys[i] > Keys[i+1]) {
            Keys[i] ↔ Keys[i+1];
            done &= false;
        }
    }          //All threads 'and' their done flag into the local variable
    return done;
}
```

Which functions may we use in a reduction?

A. Add — $a_0 + a_1 + \ldots + a_{n-1}$

B. Subtract — $a_0 - a_1 - \ldots - a_{n-1}$

C. Logical And — $a_0 \wedge a_1 \wedge \ldots \wedge a_{n-1}$

D. A and B

E. A,B and C

Which functions may we use in a reduction?

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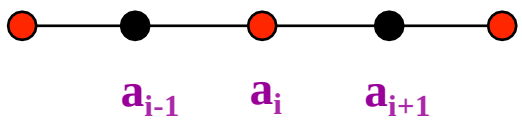
C. Logical And — $a_0 \wedge a_1 \wedge \ldots \wedge a_{n-1}$

D. A and B

E. A,B and C

Odd-Even sort in OpenMP

```
for s = 1 to MaxIter do
    done = Sweep(Keys, N, 0);
    done &= Sweep(Keys, N, 1);
    if (done) break;
end do
```




```
int  Sweep(int *Keys, int N, int OE){
    bool done=true;
#pragma omp parallel for shared(Keys) private(i) reduction(&:done)
    for (i = OE; i < N-1; i+=2) {
        if (Keys[i] > Keys[i+1]) {
            int tmp = Keys[i];
            Keys[i] = Keys[i+1];
            Keys[i+1] = tmp;
            done *= false;
        }
        return done;
}
```

-n 8Mi, -i 200, -f 50

P=1	P=2	P=4	P=8
6.09s	3.51s	2.78s	2.78s

g++ -fopenmp, on Bang

Why isn't a barrier needed between the calls to sweep( )?

A. The calls to sweep occur outside parallel sections
B. OpenMP inserts barriers after the calls to Sweep
C. OpenMP places a barrier after the "for i" loop inside Sweep()
D. A & C
E. B & C

```
for (s = 1; s<= to MaxIter; s++) {
    done = Sweep(Keys, N, 0);
    done &= Sweep(Keys, N, 1);
    if (done) break;
}

int Sweep(int *Keys, int N, int OE) {
    bool done=true;
#pragma omp parallel for shared(Keys) private(i) reduction(&:done)
    for (i = OE; i<= (N-2); i-=2) {
        if (Keys[i] > Keys[i+1]) {
            swap (&Keys[i], &Keys[i+1]);
            done &= false;
        }
    }
    return done;
}
```

Why isn't a barrier needed between the calls to sweep( )?

A. The calls to sweep occur outside parallel sections
B. OpenMP inserts barriers after the calls to Sweep
C. OpenMP places a barrier after the "for i" loop inside Sweep()
D. A & C
E. B & C

```
for (s = 1; s<= to MaxIter; s++) {
    done = Sweep(Keys, N, 0);
    done &= Sweep(Keys, N, 1);
    if (done) break;
}

int Sweep(int *Keys, int N, int OE) {
    bool done=true;
#pragma omp parallel for shared(Keys) private(i) reduction(&:done)
    for (i = OE; i<= (N-2); i-=2) {
        if (Keys[i] > Keys[i+1]) {
            swap (&Keys[i], &Keys[i+1]);
            done &= false;
        }
    }
    return done;
}
```

Another way of annotating loops + Sharing

- These examples are equivalent
- Why don't we need to declare private(i)?

```
#pragma omp parallel shared(a,b) {
#pragma omp for schedule(static)
for (int i=1; i< N-1; i++)
    a[i] = (b[i+1] – b[i-1])/2h
}
```

```
#pragma omp parallel for shared(a,b) schedule(static)
for (int i=1; i< N-1; i++)
    a[i] = (b[i+1] – b[i-1])/2h
```

- OpenMP has rules about what is shared vs private by default
  - Shared by default
    - Declared outside a private area
    - Global, static, or dynamically allocated
  - Private by default
    - Loop control variables
    - Local/Automatic variables declared within parallel area

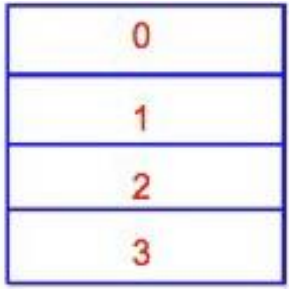
The No Wait clause

- Removes the barrier after an omp *for* loop
- Why are the results incorrect?
  - We don't know when the threads finish
  - OpenMP doesn't define the order that the loop iterations will be incorrect

```
#pragma omp parallel
{
#pragma omp for nowait
    for (int i=1; i< N-1; i++)
        a[i] = (b[i+1] – b[i-
        1])/2h
    #pragma omp for
    for (int i=N-2; i>0; i--)
        b[i] = (a[i+1] – a[i-1])/2h
 }
```

Parallelizing a nested loop with OpenMP

- Not all implementations can parallelize inner loops
- We parallelize the outer loop index

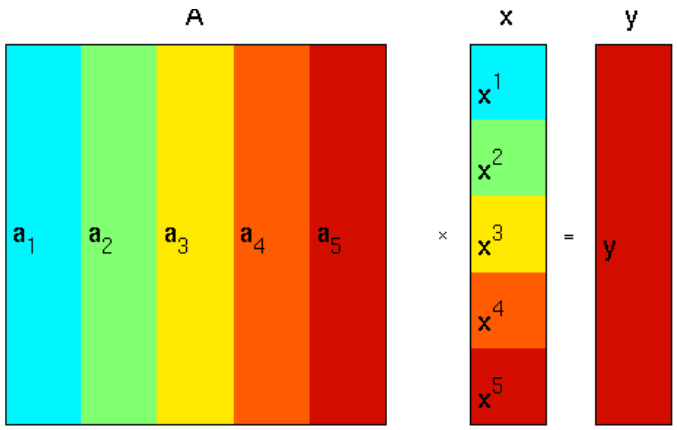



```
#pragma omp parallel private(i) shared(n)
#pragma omp for
for(i=0; i < n; i++) {
    for(j=0; j < n; j++) {
        V[i,j] = (u[i-1,j] + u[i+1,j]+ u[i,j-1]+ u[i, j+1] - h2f[i,j])/4
    }
}
```

- Generated code

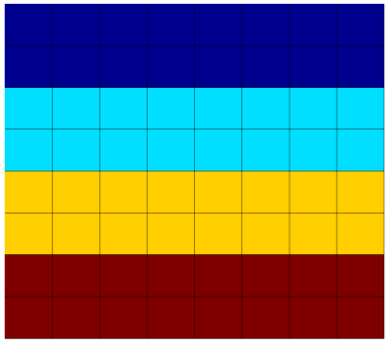
```
mymin = 1 + ($TID * n/NT),
for(i=mymin; i < mymax; i++) {
    for(j=0; j < n; j++) {
        V[i,j] = (u[i-1,j] + u[i+1,j]+ u[i,j-1]+ u[i, j+1] - h2f[i,j])/4
    }
}
Barrier();
```

An application: Matrix Vector Multiplication



Application: Matrix Vector Multiplication

```
 double **A, *x, *y;                                  // GLOBAL
#pragma omp parallel shared(A,x,N)
#pragma omp for
        for (i=0; i<N; i++){
            y[i] = 0.0;
            for (j=0; j<N; j++)
                y[i] += A[i][j] * x[j];
        }
```

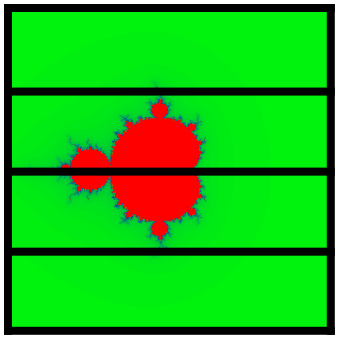


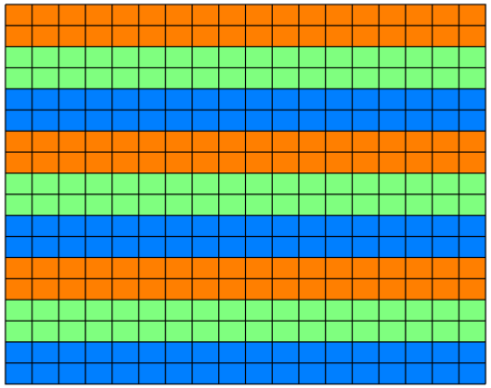
$$\begin{bmatrix} a_{00} & a_{01} & \cdots & a_{0,n-1} \\ a_{10} & a_{11} & \cdots & a_{1,n-1} \\ \vdots & \vdots & & \vdots \\ a_{i0} & a_{i1} & \cdots & a_{i,n-1} \\ \vdots & \vdots & & \vdots \\ a_{m-1,0} & a_{m-1,1} & \cdots & a_{m-1,n-1} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_{n-1} \end{bmatrix} = \begin{bmatrix} y_0 \\ y_1 \\ \vdots \\ y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots a_{i,n-1}x_{n-1} \\ \vdots \\ y_{m-1} \end{bmatrix}$$

Support for load balancing in OpenMP

- **OpenMP supports Block Cyclic decompositions with chunk size**

```
#pragma omp parallel for schedule(static, 2)
for ( int i = 0; i < n; i++ ) {
      for (int j = 0; j < n; j++ ){
            do
               z = z^2 + c
            while (|z| < 2 );
    }
}
```

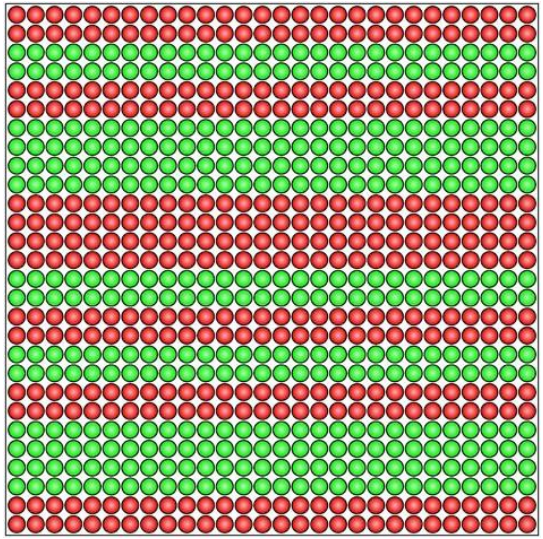




OpenMP supports self scheduling

Adjust task granularity with a chunksize

```
#pragma omp parallel for schedule(dynamic, 2)
for( int i = 0; i < n; i++ ) {
      for (int j = 0; j < n; j++ ){
            do
                z = z^2 + c
            while (|z| < 2 )
    }
}
```



Iteration to thread mapping in OpenMP

```
#pragma omp parallel shared(N,iters) private(i)
#pragma omp for
for (i = 0; i < N; i++)
    iters[i] = omp_get_thread_num();
```

# of openMP threads = 3 (no schedule)
N = 9: 0 0 0 1 1 1 2 2 2

# of openMP threads = 4, schedule(static,2):
N = 16: 0 0 1 1 2 2 3 3 0 0 1 1 2 2 3 3

# of openMP threads = 4, schedule(static,2)
N=9: 0 0 1 1 2 2 0 0 1

Initializing Data in OpenMP

- Allocate heap storage (shared) outside a parallel region
- Initialize it inside a parallel region
  - May allow it to be done in parallel.

```
double **A;
A =(double**) malloc(sizeof(double*)*N + sizeof(double)*N*N);
assert(A);

#pragma omp parallel private(j) shared(A,N)
for(j=0;j<N;j++)
    A[j] = (double *)(A+N) + j*N;

#pragma omp parallel private(i,j) shared(A,N)
for ( j=0; j<N; j++ )
   for ( i=0; i<N; ci++ )
      A[i][j] = 1.0 / (double) (i+j-1);
```

OpenMP is also an API

- But we don't use this lower level interface unless necessary
- Parallel *for* is much easier to use

```
#ifdef _OPENMP
#include <omp.h>
#endif
int tid=0, nthrds,1;
#pragma omp parallel
{
#ifdef _OPENMP
tid = omp_get_thread_num();
nthrds = omp_get_num_threads();
#endif

int i0=(n/nthrds)*tid, i1=i0+n/nthrds;
for(i=i0; i < i1; i++)
    work(i);
}
```

Summary: what does OpenMP accomplish for us?

- Higher level interface simplifies the programmer's model

- Spawn and join threads, "Outlining" code into a thread function

- Handles synchronization and partitioning

- If it does all this, why do you think we need to have a lower level threading interface?